

Evidence of finite sQGP formation time at RHIC

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Outline:

- Demonstrate where long formation time comes from
- Show its influence on experimental observables
- View on non-photonic electrons result and J/ψ puzzle
- Are there some theoretical proofs?
- Conclusions

See V.P. hep-ph/0506095, hep-ph/0509207

And

<http://www.phenix.bnl.gov/WWW/publish/pantuev/WWNuclearDynamics2006.ppt>

“pQCD-based calculations ... reproduce much of the published data on high pT hadron production in nuclear collisions.

Nevertheless, it is important to ask to what extent the data *require* this description to be the correct one.”

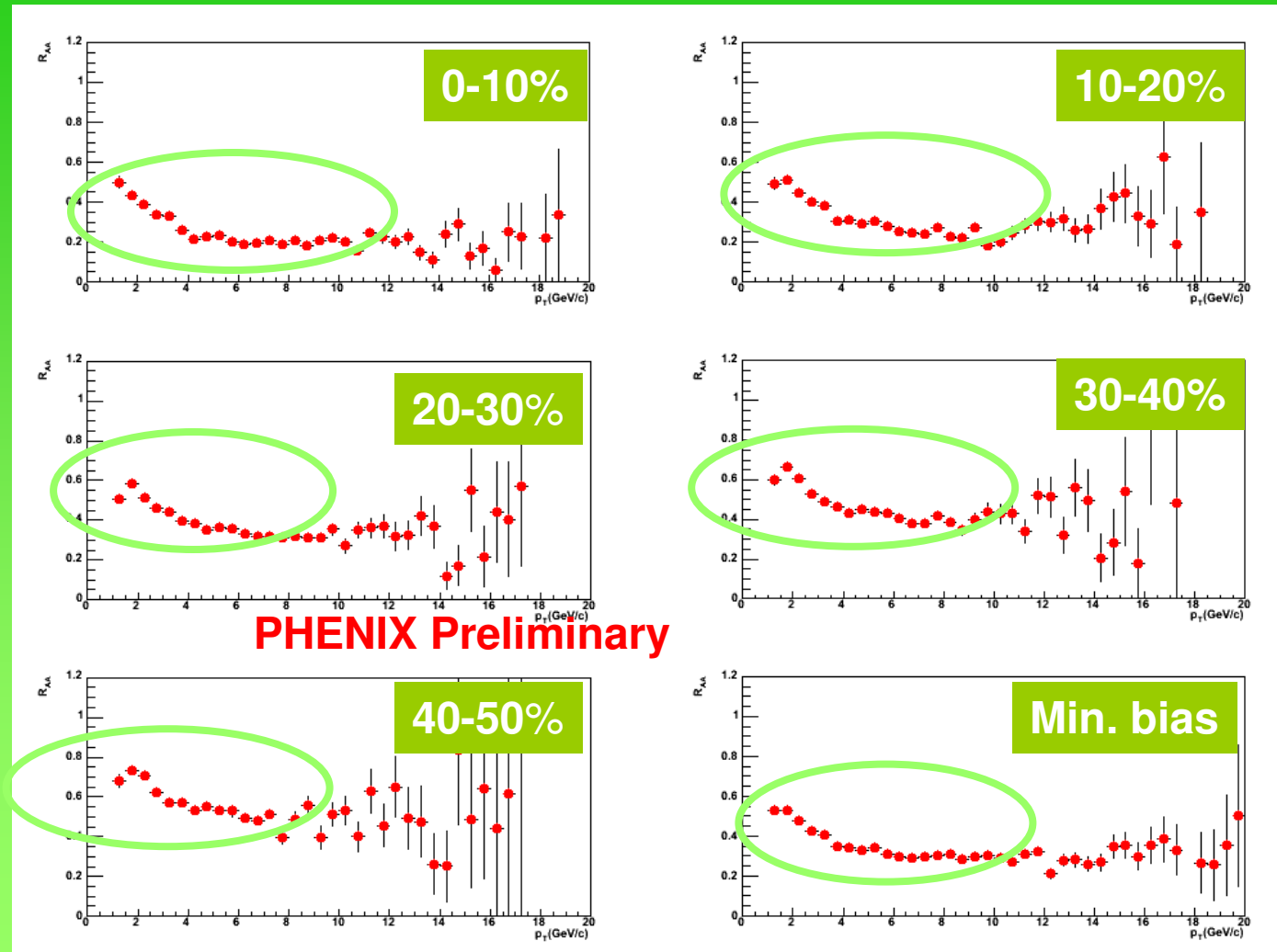
*P.Jacobs and M. van Leeuwen, QM2005
proceedings, nucl-ex/0511013*

Let's look just at experimental data and “see what we get...”

The Story, which is known for 5 years...

Nuclear modification factor $R_{AA} = \text{Yield}_{AA} / \langle N_{binary} \rangle : \text{Yield}_{pp}$

π^0 R_{AA} for
200 GeV
Au Au
Collisions

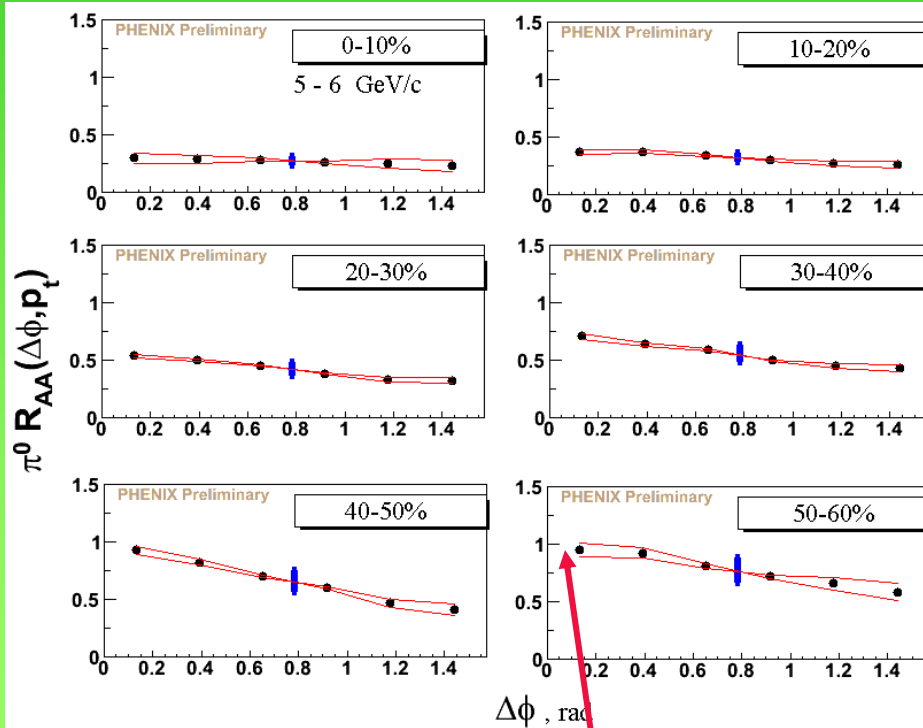


R_{AA} appears small and flat all the way to $p_T \sim 20$ GeV/c

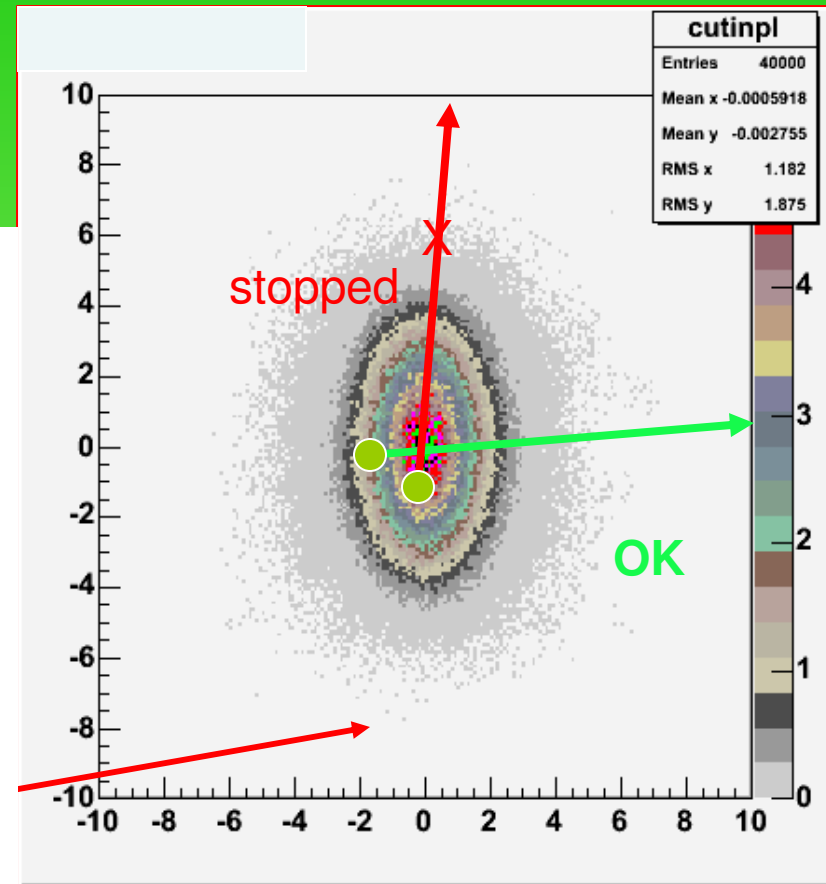
Where formation time comes from?

New quality data:

Raa for 5-6 GeV/c pions vs. ϕ in reaction plane, PHENIX QM2005, preliminary



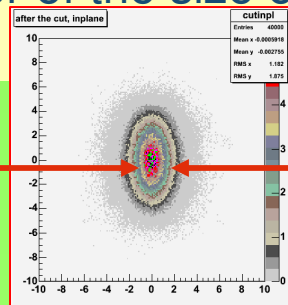
This is a key point. No absorption!?



Ncoll for 50-55% cent in x-y plane.
WS, Glauber

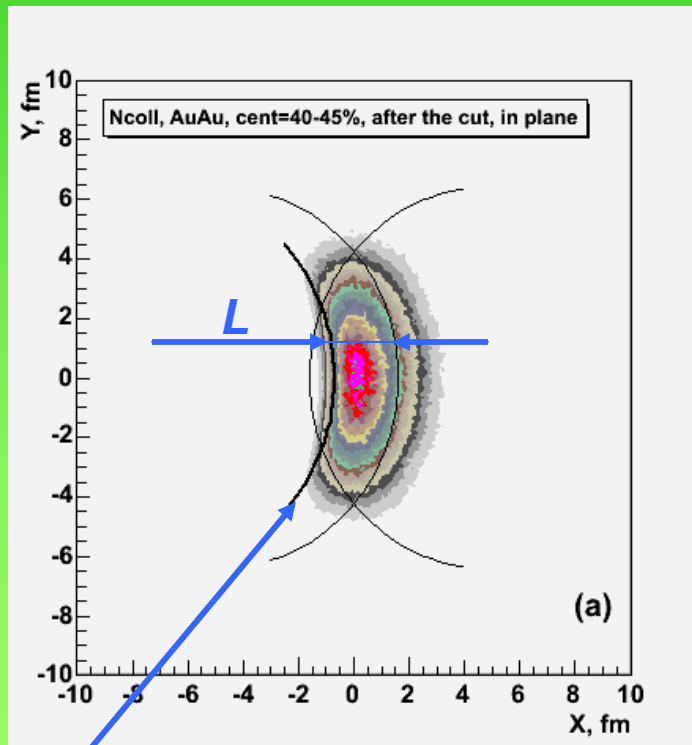
We construct a simple geometrical model:

- Monte Carlo simulation of A+A based on Glauber approach. Woods-Saxon density distribution
- Restrict to high $p_t > 4$ GeV/c pions, where R_{AA} does not depend on p_t
- Assume, all pions are produced by parton/jet fragmentation
- Number of partons/jets is proportional to N_{coll}
- Ignore longitudinal expansion (actually, I do not construct microscopic model)
- ***Jets, moving at some direction and produced not deeper than distance L will leave unmodified***
- ***Jets, produced in the core region deeper than L will be absorbed completely***
- This is pure corona jet production, but we have to find corona thickness L from experiment. L could be larger than a Woods-Saxon type skin
- L should be on the order of the size of in-plane interaction zone at 50-55% centrality, about 2-3 fm



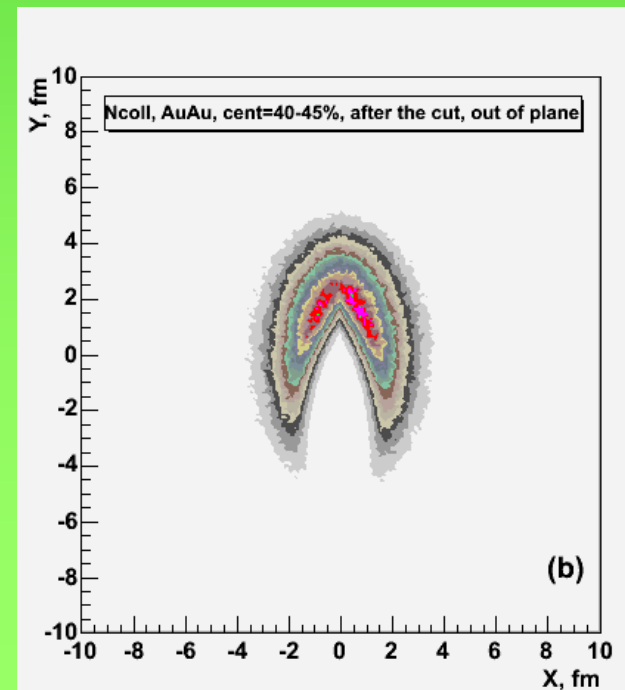
$R_{aa}(\phi)$ is **inclusive** measurement and
in a particular event you **always** look at **some angle**.

Measure from here:
out-plane, $\phi = \pi/2$

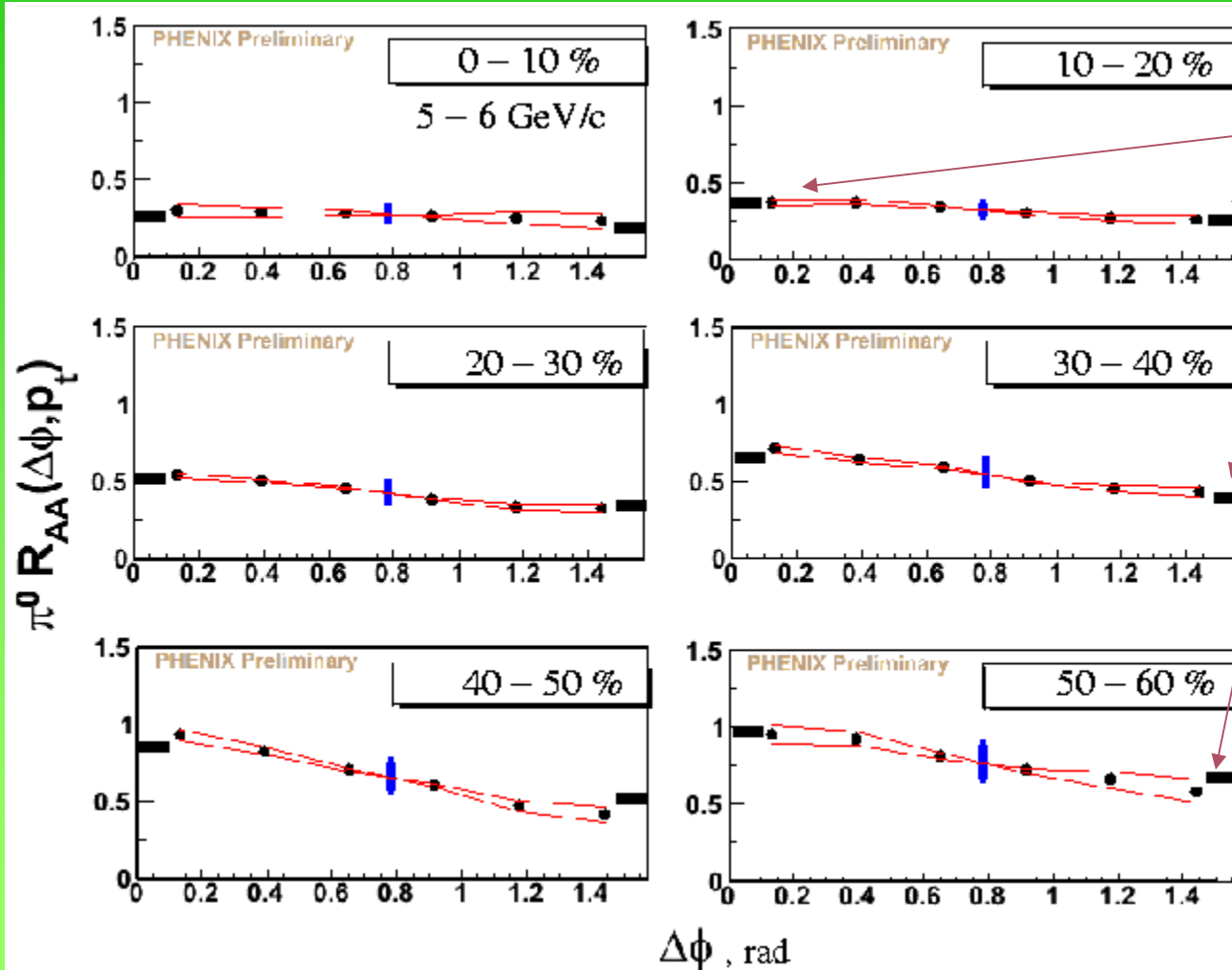


Measure from here:
in-plane, $\phi = 0$

Cutoff $L=2.3$ fm is adjusted for in-plane 50-55% centrality $R_{aa}=0.9$



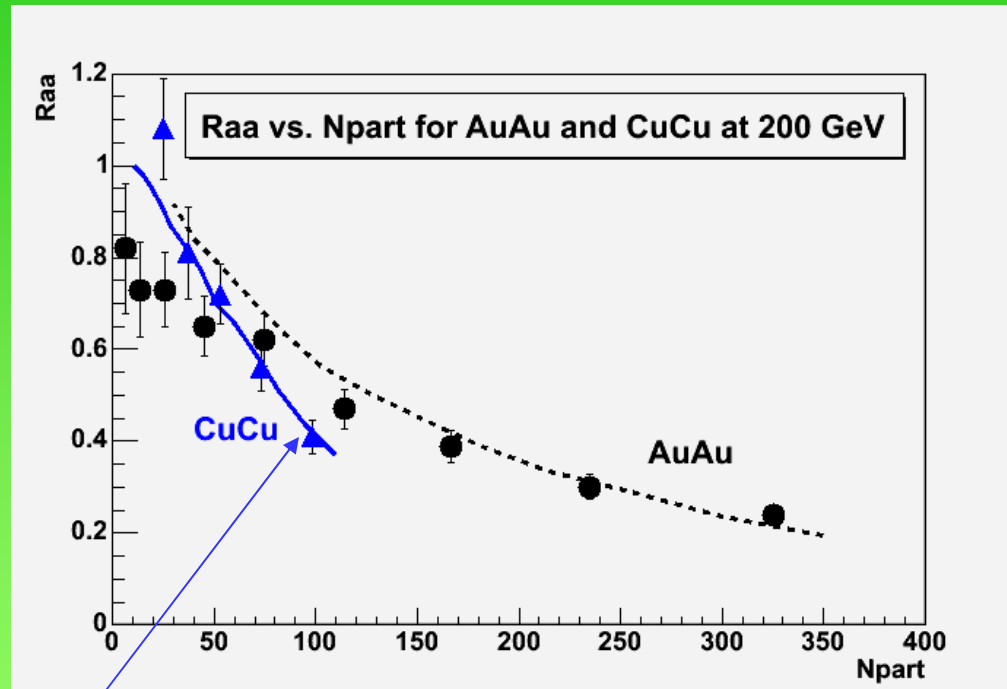
Can calculate R_{AA} as a **ratio of seen number of collisions** after the cut, **N_{coll}** , to the average total number of binary collisions, **$\langle N_{binary} \rangle$** , for particular centrality class



Black boxes -
Results of my
estimation with
 $L=2.3 \text{ fm}$

to get $R_{AA}=0.9$ at
50-55% centrality

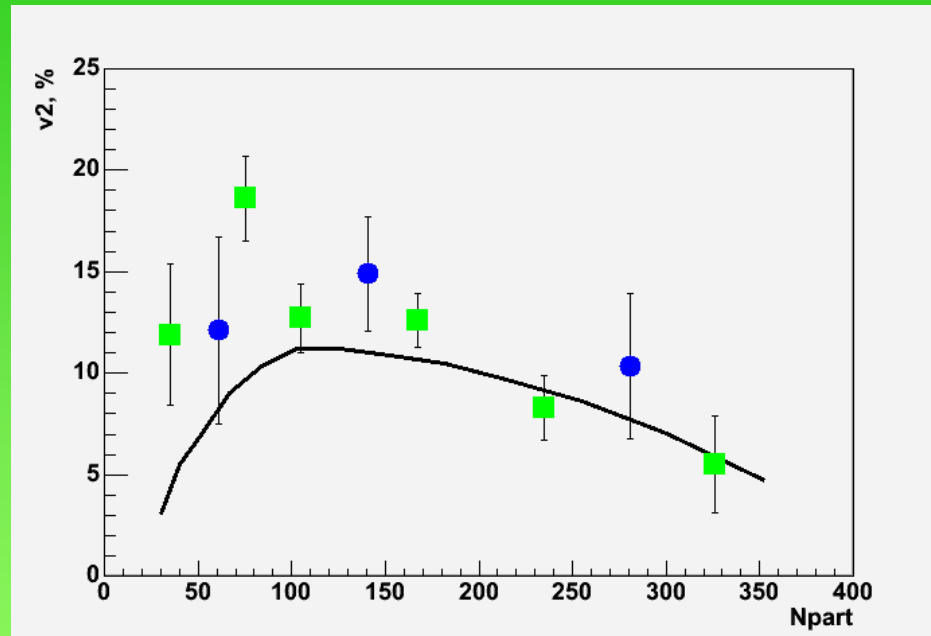
Averaged over all angles R_{aa} :



This actually was prediction!
Before QM2005, with the same
 $L=2.3$ fm

π^0 , points with error bars – experimental data.
Systematic errors are not shown

Can calculate ellipticity parameter v_2 as
jet surviving probability
in and out of plane



Data are for high pt π^0 s, PHENIX,
blue circles – 4.59 GeV/c,
green squares – 5-7 GeV/c, preliminary
No hydro/collective flow!

Additional tests:

- **Smooth cut edge**, up to 2 fm -> Very little change.
- Consider the **thickness of material integrated** over the path as a cut-off -> centrality dependence becomes very strong, can't describe the data
- Assume, **N_{part}** , not N_{coll} , is a critical value -> centrality dependence becomes weaker, $v_2 < 5\%$
- Use nucleus in the **hard sphere** model -> v_2 becomes large, about 20%

What could be a **physical interpretation** of geometrical cutoff $L=2.3 \text{ fm}$?

Our guess is that it is, actually, **formation time of strongly interacting plasma**,

$$T=L/c = 2.3 \text{ fm}/c,$$

or, at least, the time when strong parton energy loss starts.

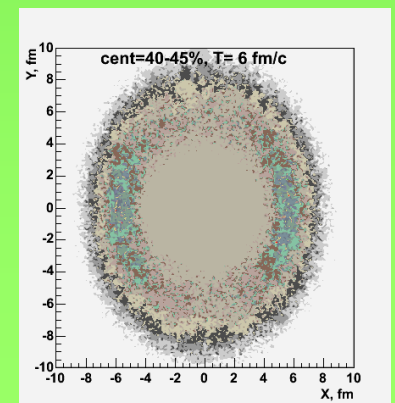
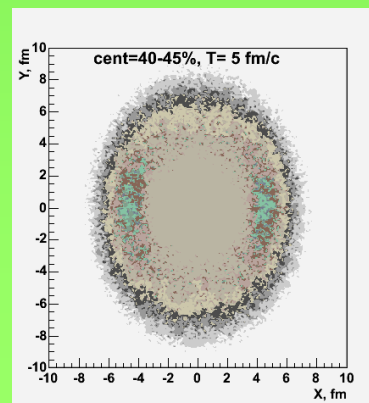
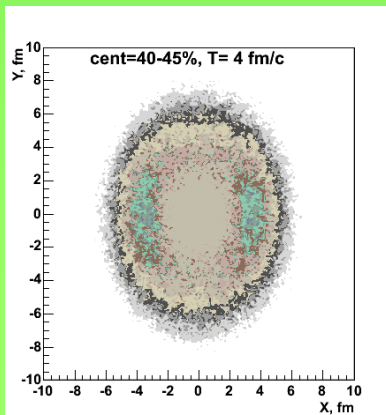
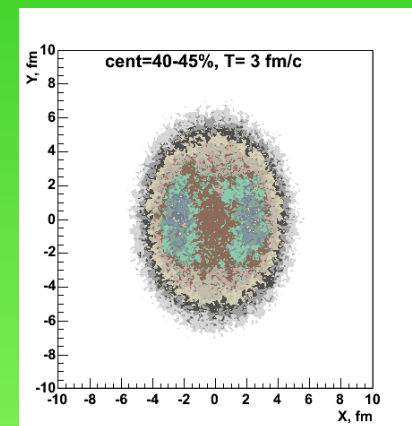
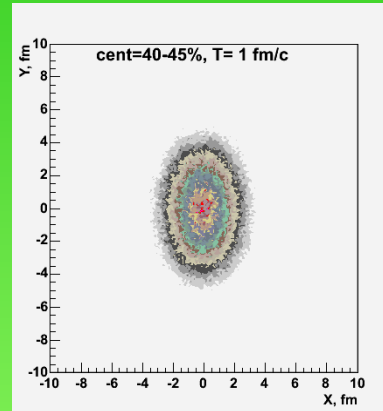
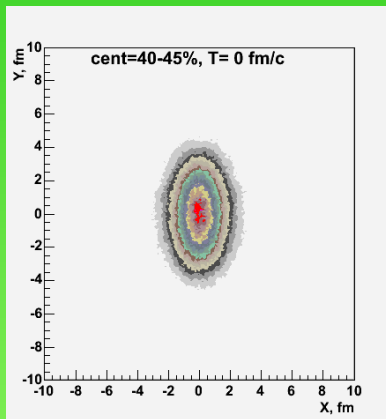
We don't want to exclude QGP formation at early stages, but it takes time to become **sQGP - strongly interacting quark-gluon plasma** .

For Au+Au at 62.4 GeV data we get $T=3.5 \text{ fm}/c$

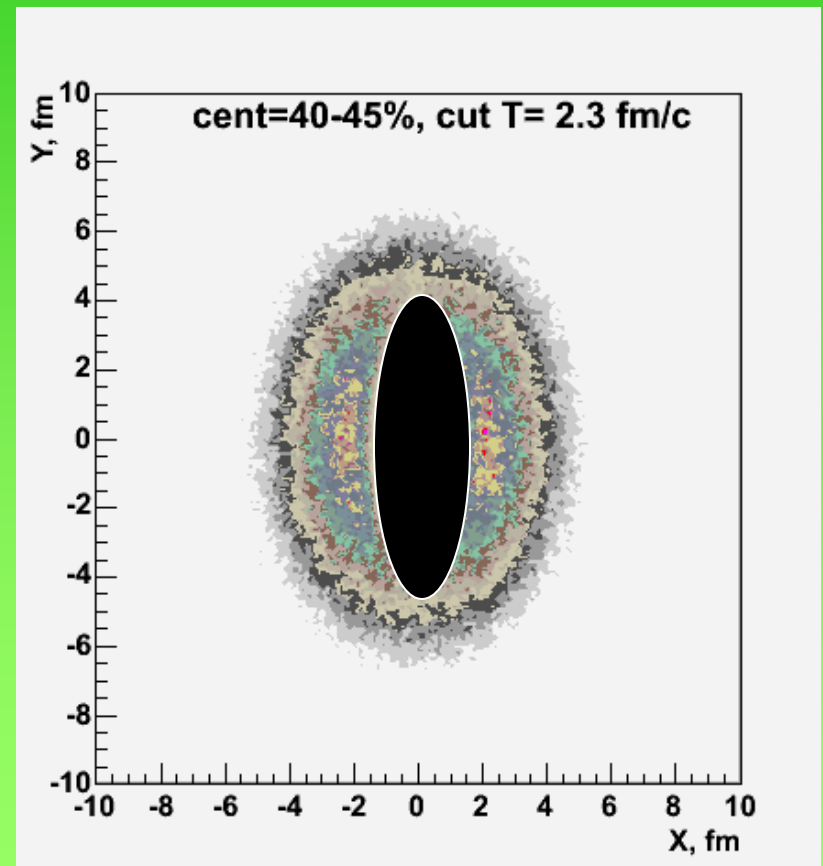
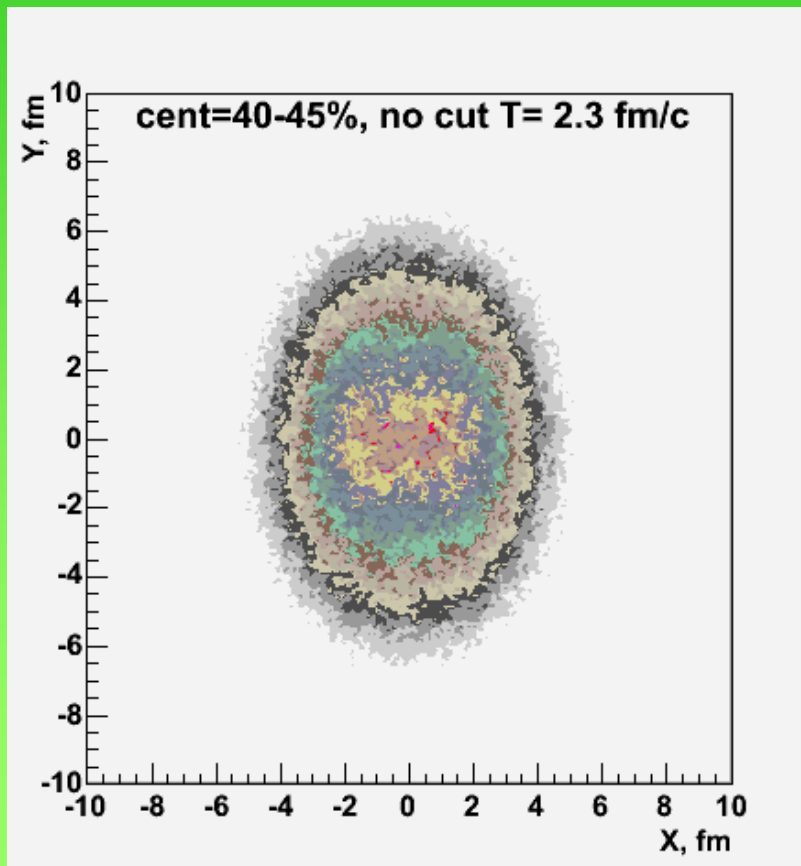
Very elegant explanation:

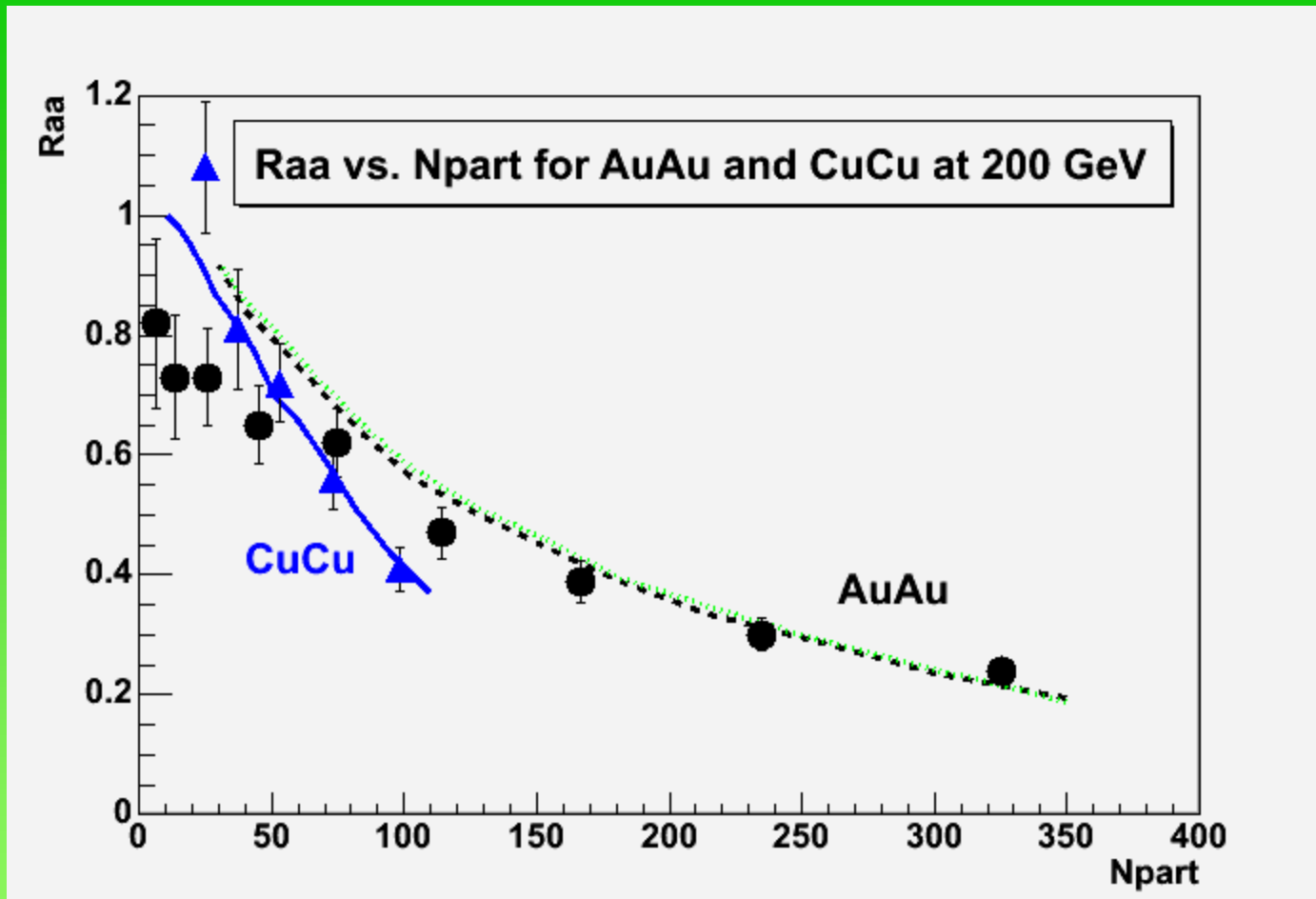
Jets, particles have time, about 2-3 fm/c, to escape from interaction region. After that time a strongly interacting dense matter is formed and this matter absorbs jets.

If it is **time**, let's make one more test: calculate **free streaming fast jets** in Au+Au at mid-rapidity with time



All jets after time 2.3 fm/c should be completely absorbed within W-S radii envelope





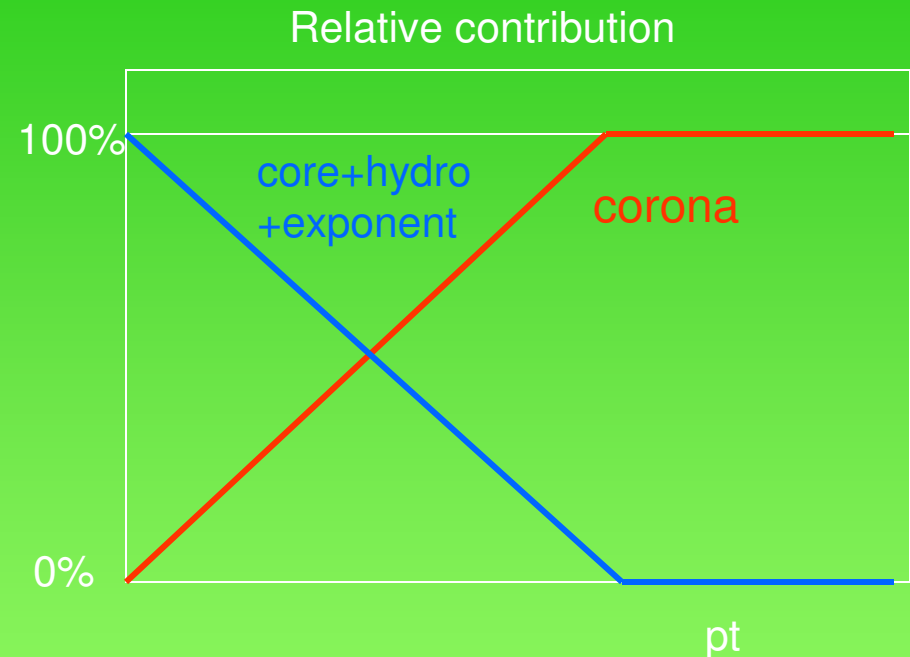
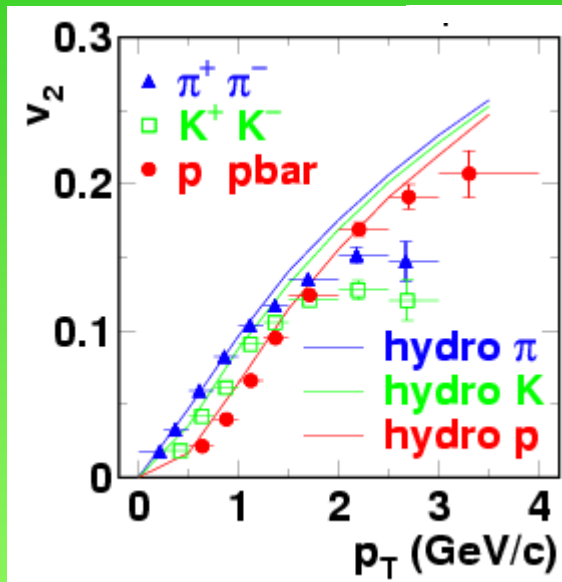
Green line is for Raa extracted with free expansion method.

Free streaming is automatically taken into account in original assumptions

List of other features and constraints induced by finite plasma formation time on some physical observables at RHIC:

1. Formed matter, sQGP, is very opaque, “black body”
2. Raa for high pt particles is determined **purely** by such a “corona” production, **not by parton partial energy loss**, or in other words,
3. **All pions** (all light hadrons) above 5 GeV/c **are produced from corona**
4. **Automatically explains flatness of Raa at high momenta**
5. $T=2.3$ fm/c was adjusted for Raa in-plane for 50-55% centrality, **but describes all Raa for Au+Au and Cu+Cu**
6. So-called, PHOBOS Npart scaling is completely described. It is accidental.
7. **No** (very weak?) dependence of **properties of near-side jets** on centrality. **All jets** are produced from **corona region**
8. There is **no flow** contribution to v_2 **at high pt**, it is **purely geometry effect**, v_2 can reach 11-12%.
9. Explains behavior of v_2 at intermediate pt region: There are **two sources** of produced particles, early **corona** and **bulk matter** itself. Hydro works well! Details follow.

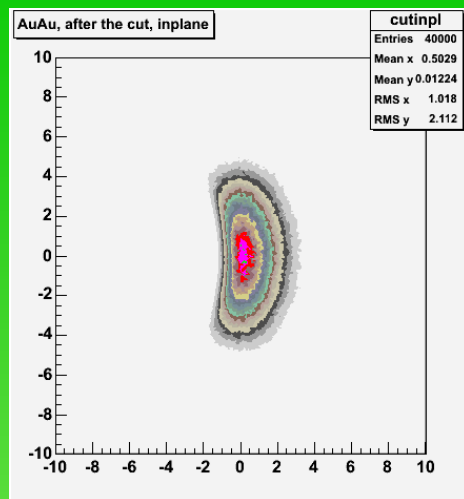
How to explain rising and falling down v_2 with momentum?



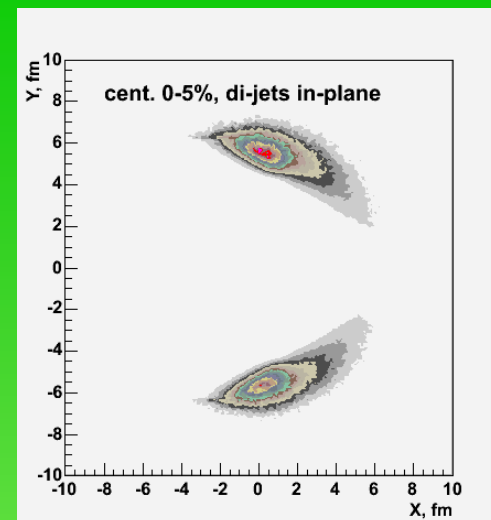
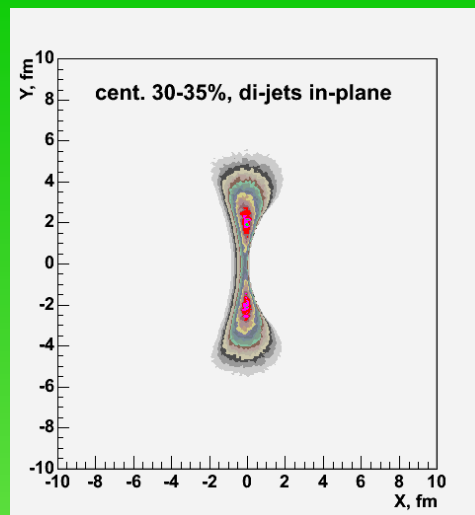
At low momentum hydro scenario produces most of particles and v_2 increases with momentum.

At high p_T , particles are produced from corona with smaller v_2 .

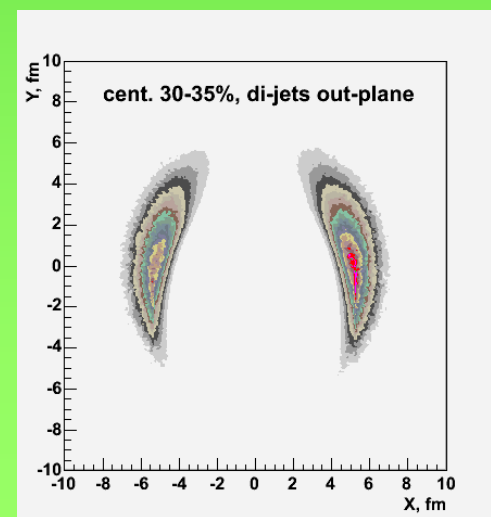
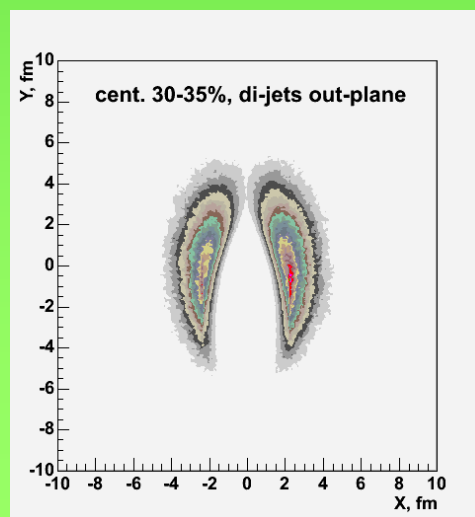
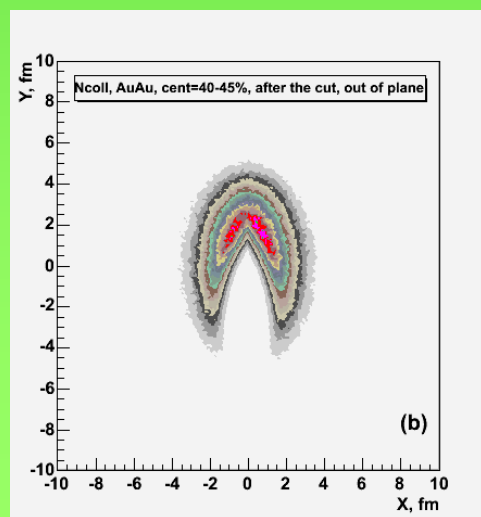
Corona contribution "dilutes" hydro v_2 at mid p_T to the value of geometry limit



**Jets,
Raa**



**Di-jets,
Iaa**

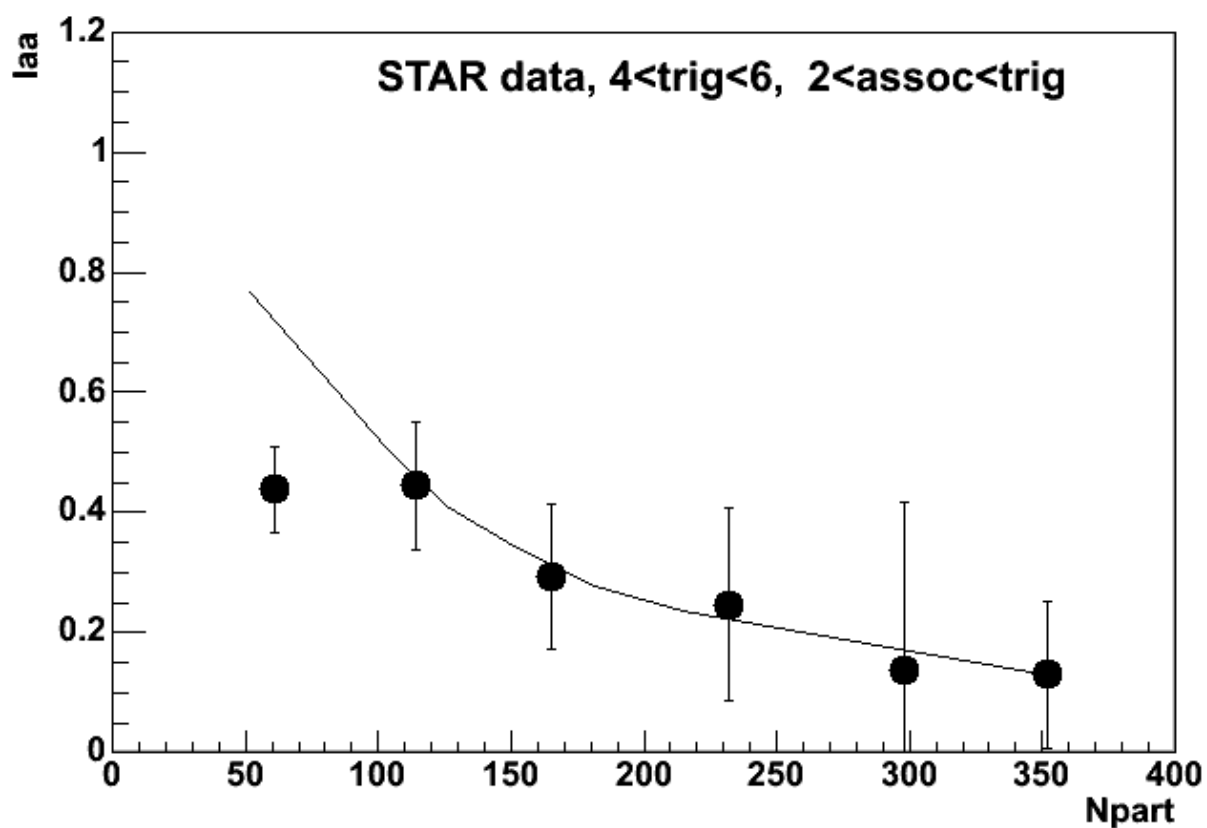


I_{aa} for $A+A$ is ratio of:

Yield of associate particles per trigger

To

Similar Yield in $p + p$

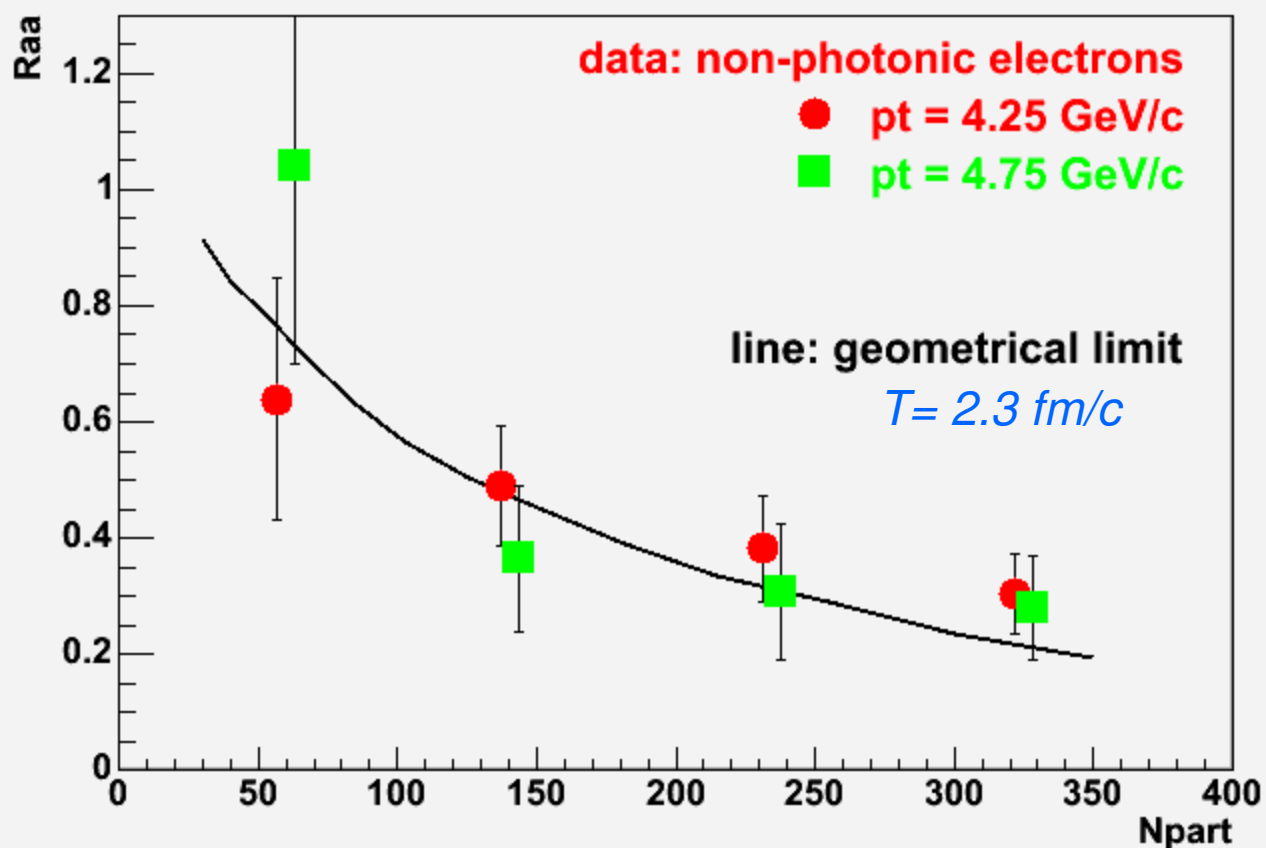


Curve –
corona
production

Continue list of consequences:

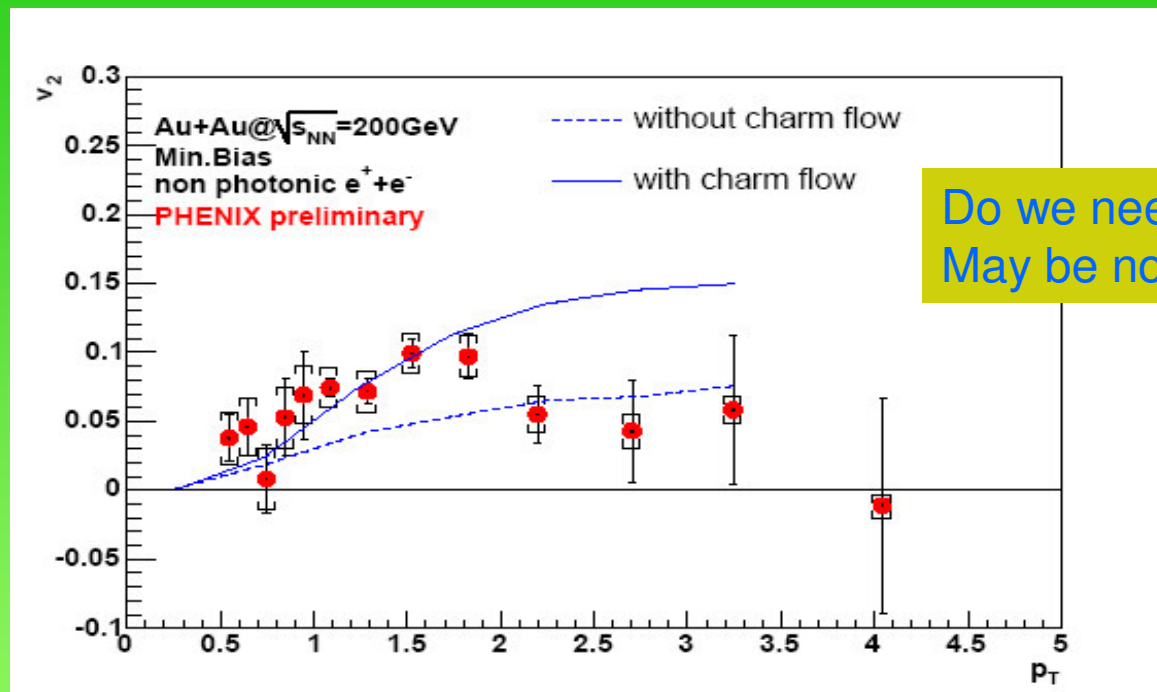
10. All di-jets at **high pt** are from corona region
11. This is why no change of Back jet properties
12. There is no “punch-through” or re-appearance of di-jets at high pt.
At lower momentum, back jet is hard to find on Mach cone “background”
13. Absorption in the core is very strong – it stops 8-10 GeV parton!
We may expect **strong c-quark suppression** as well
14. So, **c-quark corona** production must lead to **anisotropy** or v_2 ,
similar to light hadrons at high pt
15. J/ψ absorption has two stages. Should have v_2 as well

PHENIX QM2005 preliminary result, statistical errors only



The effect sits **really** on geometrical limit. It means not “just” absorption but **very** strong absorption/energy loss.

Measured v_2 is **close** to corona expectation. Most of models are in trouble



Do we need charm to flow?
May be not so much...?

Theory:
Greco, Ko, Rapp: PLB 595 (2004) 202

Do we have theoretical justification?

From *M. Thoma QM2005 talk*, [hep-ph/0509154](#): Plasma coupling parameter $\Gamma = E_{\text{pot}}/T_{\text{kin}}$, $\Gamma \ll 1$ for gas, $\Gamma \gg 1$ crystal. At RHIC $\Gamma = 1.5 - 6$, more like liquid. There should be Relaxation time.

So, Needs Time to re-order to form long range correlations. *Vapor needs time to make droplets and liquid.*

Empirically, we see very strong absorption, some theories prove it:

S.-J. Sin & I. Zahed, [Phys.Lett. B608\(2005\)265](#): use AdS/CFT duality to overcome problem of strong coupling. "... the quark-gluon liquid is very opaque. High energy jets at RHIC would not make it beyond 1/3 fm"

E. Shuryak goes even beyond "liquid" sQGP, introducing [polymer chains](#). Jet energy loss is small "until the matter cools down" which needs some latent time. [J. Lia & E. Shuryak, hep-ph/0508035](#)

For conclusions:

- Experimental data lead to **inevitable** conclusion to the existence of a 2-3 fm/c formation time of Strongly interacting QGP at 200 GeV
- Parton absorption in sQGP is VERY strong
- We don't have yet a solid theoretical justification of such a long time
- **The existence of formation time is a direct sign that sQGP is actually formed at RHIC**
- Formation time gets longer at lower energy: 2.3 fm/c at 200 GeV, 3.5 fm/c at 62 GeV.
- At even lower energy, formation time is so long that sQGP can't be formed at all because of fast longitudinal expansion

backup

Wild guess about beam energy dependence of T:

If relativistic rise of NN total cross section is purely contribution from hard scattering (this is a guess)

Estimate NN total cross section by formula provided by Regge theory:

$\sqrt{s} = 20 \text{ GeV}$	38.6 mb	hard scattering contribution $\Delta\sigma = 0$??
$\sqrt{s} = 62.4 \text{ GeV}$	43.65 mb	$\Delta\sigma = 5 \text{ mb}$
$\sqrt{s} = 200 \text{ GeV}$	51.55 mb	$\Delta\sigma = 13 \text{ mb}$
$\sqrt{s} = 5500 \text{ GeV}$	87.2 mb	$\Delta\sigma = 48.6 \text{ mb}$

If formation time T is proportional to the mean **distance** between HARD scatterings (kind of, to make *a la* Shuryaks bonds),

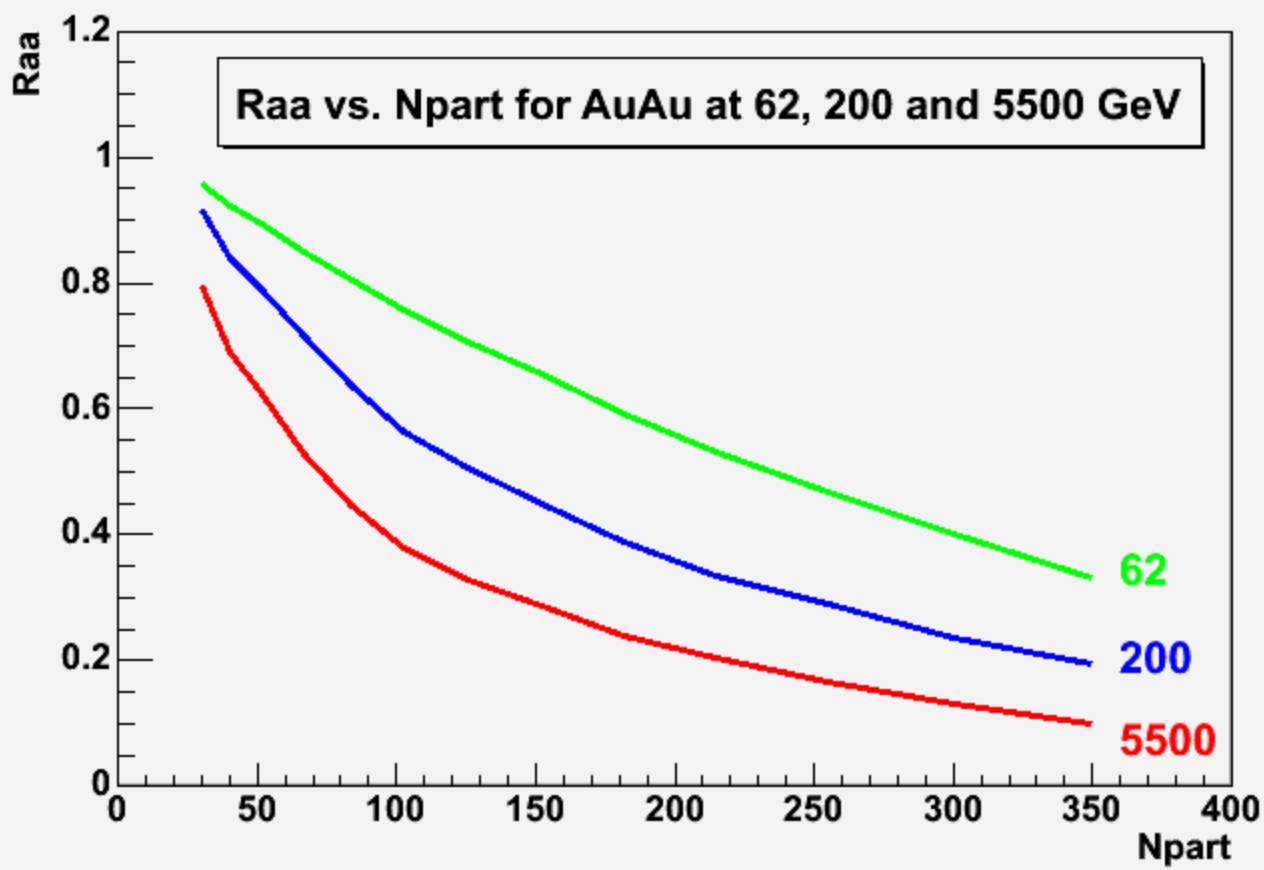
it should be $T \sim 1/\sqrt{\Delta\sigma}$

If at 200 GeV we have $T=2.3 \text{ fm/c}$, we should get

$T = 3.6 \text{ fm/c}$ at 62 GeV

$T = 1.2 \text{ fm/c}$ at 5500 GeV at CERN

My estimate for LHC:



the 1990s, the number of people in the UK who are aged 65 and over has increased by 1.5 million (1990–2000) and is projected to increase by a further 1.5 million by 2020 (Office for National Statistics 2001). The number of people aged 65 and over in the UK is projected to increase from 10.5 million in 2000 to 13.5 million in 2020.

There is a growing awareness of the need to develop strategies to meet the needs of the ageing population. The Department of Health (2000) has published a strategy for ageing, which sets out the government's commitment to improve the lives of older people. The strategy is based on the following principles:

- Older people should be able to live independently and actively in their own homes.
- Older people should be able to participate in the community and in the life of the country.
- Older people should be able to enjoy a good standard of living.

The strategy also sets out a number of key objectives, including: to improve the health and well-being of older people; to improve the quality of life of older people; to improve the financial security of older people; and to improve the social inclusion of older people.

The strategy is a key document for the development of policies and services for older people. It provides a framework for the development of policies and services that are based on the principles and objectives of the strategy.

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